

# REVIEW OF THE WORKSHOP ON LOW-COST POLYSILICON FOR TERRESTRIAL PHOTOVOLTAIC SOLAR CELL APPLICATIONS

JET PROPULSION LABORATORY

R. Lutwack

- SILICON MATERIAL TASK OF THE DOE/FSA PROJECT  
R. LUTWACK, CHAIRMAN (JET PROPULSION LABORATORY)
- SESSION I: POLYSILICON MATERIAL REQUIREMENTS  
CHAIRMAN: J. McCORMICK (HEMLOCK SEMICONDUCTOR CORP.)
  - EFFECTS OF IMPURITIES ON SILICON SOLAR CELL PERFORMANCE  
R. HOPKINS (WESTINGHOUSE R&D CENTER)
  - REQUIREMENTS FOR HIGH-EFFICIENCY SOLAR CELLS  
C.T. SAH (UNIVERSITY OF ILLINOIS)
- SESSION II: ECONOMICS  
CHAIRMAN: R. PELLIN (CONSULTANT)
  - ECONOMICS OF THE POLYSILICON PROCESS: A VIEW FROM JAPAN  
Y. SHIMIZU (OSAKA TITANIUM CO., LTD.)
  - ECONOMICS OF POLYSILICON PROCESSES  
C. YAWS (LAMAR UNIVERSITY)
  - SENSITIVITY ANALYSIS FOR SOLAR PANELS  
R. ASTER (JET PROPULSION LABORATORY)
- SESSION III: PROCESS DEVELOPMENTS IN THE USA  
CHAIRMAN: P. MAYCOCK (PV ENERGY SYSTEMS)
  - DEVELOPMENT OF THE SILANE PROCESS FOR THE PRODUCTION OF  
LOW-COST POLYSILICON  
S. IYA (UNION CARBIDE CORP.)
  - FLUIDIZED-BED DEVELOPMENT AT JET PROPULSION LABORATORY  
G. HSU (JET PROPULSION LABORATORY)
  - FLUIDIZED-BED REACTOR MODELING FOR PRODUCTION OF SILICON  
BY SILANE PYROLYSIS  
M. DUDUKOVIC (WASHINGTON UNIVERSITY AT ST. LOUIS)
  - SILICON PRODUCTION IN AN AEROSOL REACTOR  
R. FLAGAN (CALIFORNIA INSTITUTE OF TECHNOLOGY)

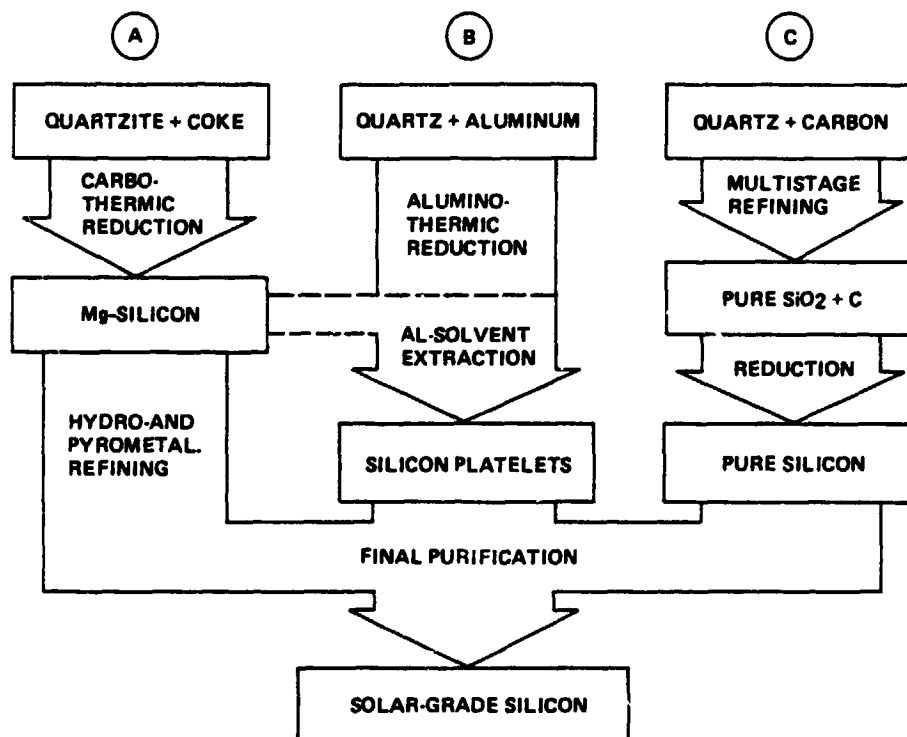
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## SILICON MATERIALS

- SESSION IV: PROCESS DEVELOPMENTS, INTERNATIONAL  
CHAIRMAN: R. LUTWACK (JET PROPULSION LABORATORY)
  - PROCESSES AND PROCESS DEVELOPMENTS IN JAPAN  
T. NODA (OSAKA TITANIUM CO., LTD.)
  - PROCESSES AND PROCESS DEVELOPMENTS IN TAIWAN  
H-L. HWANG (NATIONAL TSING HUA UNIVERSITY)
  - REFINING OF METALLURGICAL-GRADE SILICON  
J. DIETL (HELIOTRONICS GmbH)
  - SOLAR-GRADE SILICON PREPARED BY CARBOTHERMIC REDUCTION OF SILICA  
H. AULICH (SIEMENS AG)
  - A METALLURGICAL ROUTE TO SOLAR-GRADE SILICON  
A. SCHEI (ELKEM A/S, R&D CENTER)
  - SOLAR SILICON FROM DIRECTIONAL SOLIDIFICATION OF MG SILICON PRODUCED VIA THE SILICON CARBIDE ROUTE  
M. RUSTONI (ENICHIMICA)
- SESSION V: CHAIRMAN: A. BRIGLIO (JET PROPULSION LABORATORY)
  - CHARACTERIZATION OF SOLAR-GRADE SILICON PRODUCED BY THE  $\text{SiF}_4$ -Na PROCESS  
A. SANJURJO (SRI INTERNATIONAL)
  - A SILANE-BASED POLYSILICON PROCESS  
P. GRAYSON (EAGLE-PICHER INDUSTRIES, INC.)
  - SILICON PURIFICATION USING A Cu-Si ALLOY SOURCE  
R. POWELL (SOLAR ENERGY RESEARCH INSTITUTE)
  - FORUM: POLYSILICON PROCESS TECHNOLOGY  
CHAIRMAN: H. AULICH (SIEMENS AG)

## SILICON MATERIALS

### Different Approaches to Large-Scale Production of Solar-Grade Silicon



(J. DIETL, WACKER HELIOTRONIC)

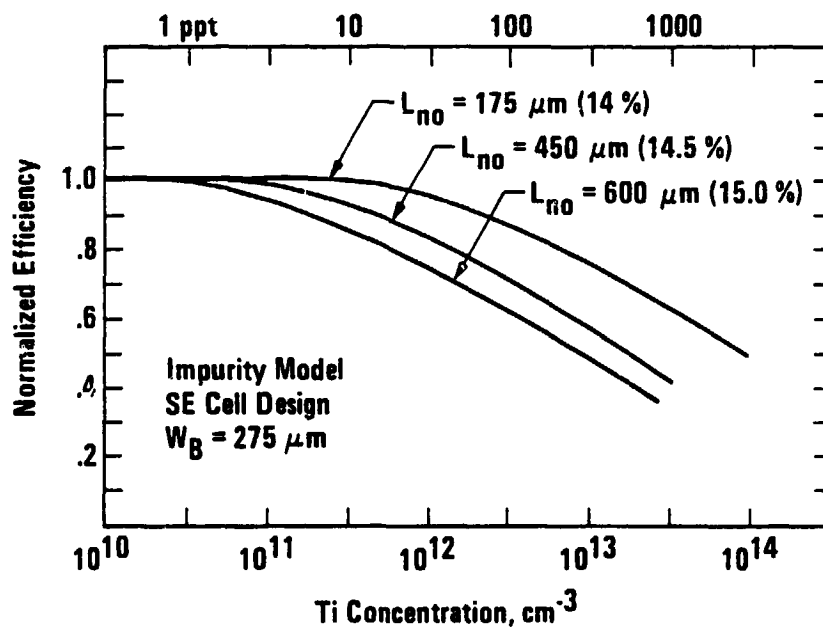
- SESSION VI: POLYSILICON MARKET AND FORECASTS  
CHAIRMAN: M. PRINCE (U. S. DEPARTMENT OF ENERGY)
- SEMICONDUCTOR MARKET  
R. PELLIN (CONSULTANT)
- SILICON REQUIREMENTS OF THE PHOTOVOLTAIC SOLAR CELL MARKET  
P. MAYCOCK (PV ENERGY SYSTEMS)
- FORUM: POLYSILICON MARKETS  
CHAIRMAN: J. LORENZ (CONSULTANT)

## SILICON MATERIALS

### Key Discussion Topics During Forums

- PRIMARY OBJECTIVE - LOW COST Si vs HIGH CELL EFFICIENCY
- PROCESS DEVELOPMENT OBJECTIVE - CVD Si vs SOLAR GRADE Si
- COMPETITION FROM AMORPHOUS Si
- Si SOURCE - SCRAP Si vs LOW COST Si

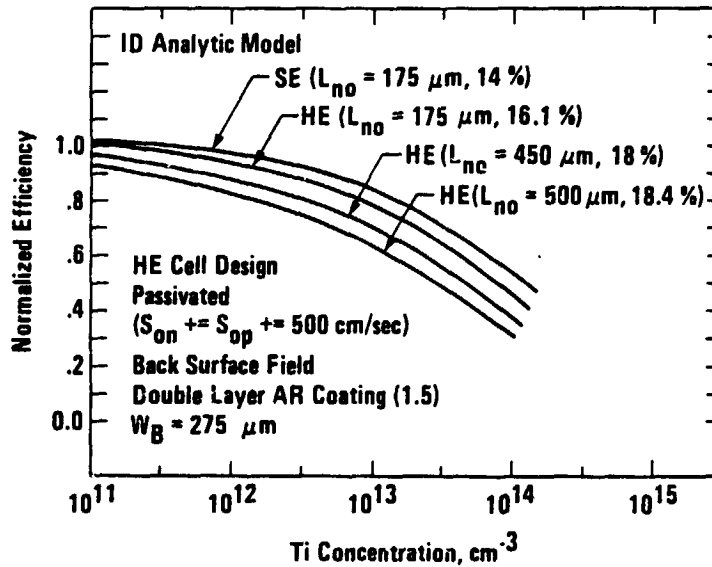
### Cell Efficiency Variation with Titanium Concentration for Various Initial Base Diffusion Lengths



(R. HOPKINS, WESTINGHOUSE RESEARCH CENTER)

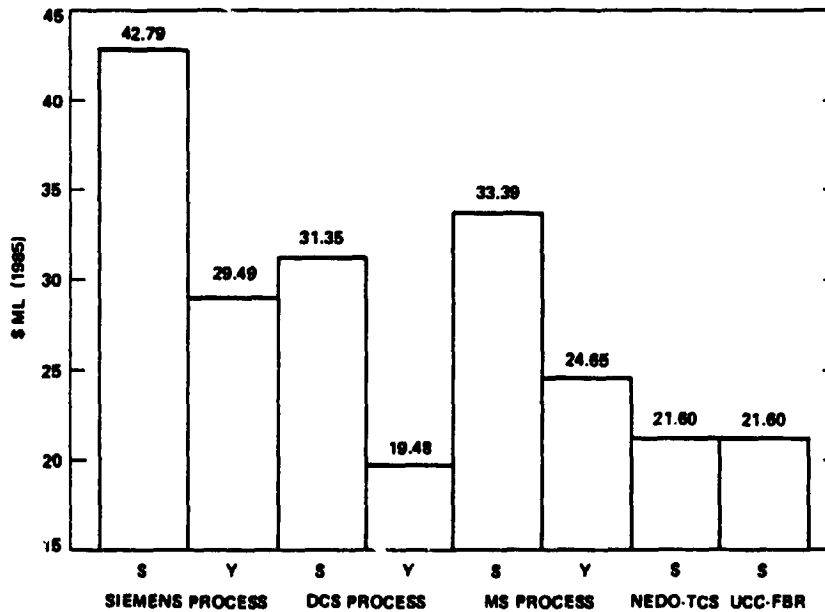
## SILICON MATERIALS

### Variation in Cell Performance with Titanium Concentration: High-Efficiency Cell Design



(R. HOPKINS, WESTINGHOUSE RESEARCH CENTER)

### Product Costs of Polysilicon Processes



(Y. SHIMIZU, OSAKA TITANIUM CO., LTD.)  
(C. YAWS, LAMAR UNIVERSITY)

# SILICON MATERIALS

## Comparisons of Analyses

|               | SiH <sub>4</sub> -CVD |       |      | SiH <sub>2</sub> Cl <sub>2</sub> -CVD |       |       |
|---------------|-----------------------|-------|------|---------------------------------------|-------|-------|
|               | Y                     | S     | Δ    | Y                                     | S     | Δ     |
| UTILITIES*    | 3.87                  | 7.60  | 3.73 | 4.86                                  | 10.20 | 5.34  |
| LABOR         | 1.90                  | 1.80  | -.1  | 1.37                                  | 1.80  | .43   |
| RAW MATERIALS | 2.91                  | 3.94  | 1.03 | 3.34                                  | 4.52  | 1.18  |
| OVERHEAD      | 1.81                  | 3.20  | 1.39 | 1.20                                  | 2.98  | 1.78  |
| GENERAL       | 3.21                  | 4.36  | 1.15 | 2.54                                  | 4.09  | 1.55  |
|               | ΣΔ                    |       | 7.21 |                                       |       | 10.28 |
| PRODUCT COST  | 24.65                 | 33.39 | 8.74 | 19.48                                 | 31.35 | 11.87 |
| * SHIMIZU (S) | 6¢/kwh                |       |      |                                       |       |       |
| YAWS (Y)      | 5¢/kwh                |       |      |                                       |       |       |

## Silicon Granule Manufacturing Results (1984)

| ITEMS               |              | TARGETS | RESULTS   |         |
|---------------------|--------------|---------|-----------|---------|
|                     |              |         | OVERALL ° | BEST °° |
| TOTAL REACTION TIME | (hr)         | --      | 4,377     | 632     |
| MANUFACTURED Si     | (kg)         | --      | 8,349     | 1,504.7 |
| TCS CONCENTRATION   | (%)          | --      | 36.5      | 42.3    |
| POWER CONSUMPTION   | (kwh/kg. Si) | 30      | 28.32     | 21.30   |
| TCS CONSUMPTION     | (kg/kg. Si)  | 20      | 18.72     | 18.94   |
| Si YIELD            | (%)          | 20      | 18.3      | 21.5    |

° YEARLY PERFORMANCE

°° BEST PERFORMANCE

(T. NODA, OSAKA TITANIUM CO., LTD.)

## SILICON MATERIALS

### Worldwide Module Sales (Factory Prices - 1985\$)

|       | <u>1983</u> | <u>1984</u> | <u>1985</u> | <u>1986</u>        | <u>1988</u> | <u>1990</u>    | <u>1995</u>  | <u>MT</u>              | <u>Si</u> |
|-------|-------------|-------------|-------------|--------------------|-------------|----------------|--------------|------------------------|-----------|
| MWp   | 22          | 22          | 26          | 60 (1)<br>35 (2)   | 150<br>50   | 300 *<br>107 * | 975<br>310 * | (5850 MT)<br>(1116 MT) |           |
| \$/Wp | 8           | 7           | 6.50        | 5 (1)<br>6 (2)     | 4<br>5      | 3<br>4.50      | 2<br>3       |                        |           |
| \$(M) | 176         | 155         | 170         | 300 (1)<br>210 (2) | 600<br>250  | 900<br>480     | 1950<br>930  |                        |           |

(1) U. S. TAX CREDITS EXTENDED TO 1989

(2) U. S. TAX CREDITS EXPIRE AFTER 1985

\* INCLUDES JAPANESE GRID-CONNECTED PV POWERED HOUSES

(P. MAYCOCK, CONSULTANT)

### A Free World Forecast for Silicon Material

| <u>YEAR</u> | <u>SILICON<br/>DEVICE<br/>USAGE<br/>\$</u> | <u>SINGLE<br/>CRYSTAL<br/>METRIC<br/>TONS</u> | <u>POLYSILICON<br/>USAGE<br/>METRIC<br/>TONS</u> | <u>POLYSILICON<br/>CAPACITY<br/>METRIC<br/>TONS</u> |
|-------------|--|---|--|---|
| 1974        | 5,750                                      | 522   | 871  |   |
| 1975        | 5,170                                      | 533   | 921  |   |
| 1976        | 6,545                                      | 702   | 1,170  |   |
| 1977        | 8,610                                      | 796   | 1,326  | 2,395   |
| 1978        | 9,905                                      | 1,001   | 1,668  | 2,445   |
| 1979        | 11,900                                     | 1,289   | 2,148  | 2,740   |
| 1980        | 14,120                                     | 1,387   | 2,312  | 3,760   |
| 1981        | 15,100                                     | 1,515   | 2,568  | 4,410   |
| 1982        | 16,460                                     | 1,793   | 3,092  | 5,270   |
| 1983        | 20,822                                     | 2,718   | 4,853  | 5,650   |
| 1984        | 30,124                                     | 3,090   | 5,617  | 6,060   |
| 1985        | 25,000                                     | 3,039   | 5,525  | 6,470   |
| 1986        | 29,000                                     | 3,781   | 6,875  | 8,540   |
| 1987        | 38,000                                     | 4,957   | 9,013  | 9,320   |
| 1988        | 50,000                                     | 5,647   | 10,457   | 12,520  |
| 1989        | 65,000                                     | 7,860   | 14,292   | 15,120  |
| 1990        | 80,300                                     | 9,936   | 18,067   | 16,820  |

(R. PELLIN, CONSULTANT)